Cadet: A High Data Rate Software Defined Radio for SmallSat Applications

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ABSTRACT

The government and private sectors are showing more interest in SmallSats for a wider range of missions. However, mission planners are discovering that even relatively simple missions are generating significant amounts of data, and that a communication infrastructure that supports high data rates must be considered early in mission conceptualization and project planning.

In answer to these emerging communication needs, L-3 Communications, in conjunction with Utah State University – Space Dynamics Laboratory, developed the Cadet Radio for the Dynamic Ionosphere CubeSat Experiment (DICE) space weather program. DICE was successfully launched in October 2011, and the Cadet radios are currently down-linking mission data at 3 Mbps to the NASA Wallops Island ground station and the SRI ground station in Palo Alto, California.

Cadet was designed from the ground up as a very low size, weight, and power (SWAP) software defined radio (SDR). It was also conceived as an element of a communication infrastructure which would be adaptable to various mission needs, and provide an affordable solution through a common core design.

The ground communication infrastructure must also be included in SmallSat mission planning. Further community development of an integrated ground infrastructure will greatly improve the effectiveness and affordability of future SmallSat missions.

INTRODUCTION TO L-3 COMMUNICATION SYSTEMS - WEST

L-3 Communications Systems – West (L-3 CSW) develops high-bandwidth, software-programmable communication architectures for ground, airborne, and space systems. L-3 CSW also develops the network communications that can link these systems across their diverse missions and domains.

Airborne systems developed by L-3 CSW include mission-critical communications systems for the U-2 reconnaissance aircraft, and Predator and Global Hawk UAVs; as well as small tactical datalinks for small tactical UAVs. L-3 CSW is relatively new to the space communications field but has quickly established an excellent track record with the TacSat 2 and 3 missions, the Operationally Responsive Space One (ORS-1) satellite, and the Oct 2011 launch of the Space Dynamics Lab's Dynamic Ionosphere CubeSat Experiment (DICE) mission.

The tactical systems L-3 CSW provides have inherent characteristics which match well with small satellites, including requirements for low cost; low size, weight, and power (SWAP); a responsive acquisition mechanism; and rapid adaptation to mission needs.

Finally, L-3 CSW has a history of strong university relations. University program requirements have many similarities to tactical mission requirements: low-cost, innovation, and short schedules. When USU SDL approached L-3 CSW with a request to build a communications system for the DICE CubeSat mission, L-3 CSW quickly provided a competitive solution to this emerging mission need.

DICE SUMMARY

In the early morning of Friday, October 28, 2011, a NASA Delta II rocket launched from Vandenberg Air Force Base in California. This rocket carried the NASA Suomi National Polar-orbiting Partnership (NPP) weather satellite plus six CubeSats built by the Space Dynamics Lab (SDL) / Utah State University, Auburn University, Montana State University, and the University of Michigan. All CubeSats were successfully deployed in their intended 809 x 457 km orbits at 102 degrees inclination.

The SDL mission consists of two CubeSats for the National Science Foundation-sponsored DICE mission. DICE is an advanced space weather mission, designed to collect significant amounts of data on space weather phenomena that have a real impact on global communication and navigation infrastructures.

DICE was allowed to use government radio bands consistent with being a NSF funded mission. Cadet was developed for DICE as a half-duplex UHF radio system to provide the first high speed communications system for a CubeSat. Each Cadet continuously listens for ground station commands, which switch it into transmit mode for a commanded period of time after which it returns to listen mode. Therefore, the spacecraft modem is fully controlled by the ground station and the spacecraft does not autonomously turn on the modem's transmitter. All Space-to-Earth communications are responses to ground station commands that request data packets from the Cadet radio. Both spacecraft use identical up- and downlink frequencies but have unique logical addresses decoded by the radio. The primary ground station is at the NASA Wallops Island Range on the east coast with a secondary/backup at SRI on the west coast. A line diagram of the communications radio systems is provided in Figure 1.

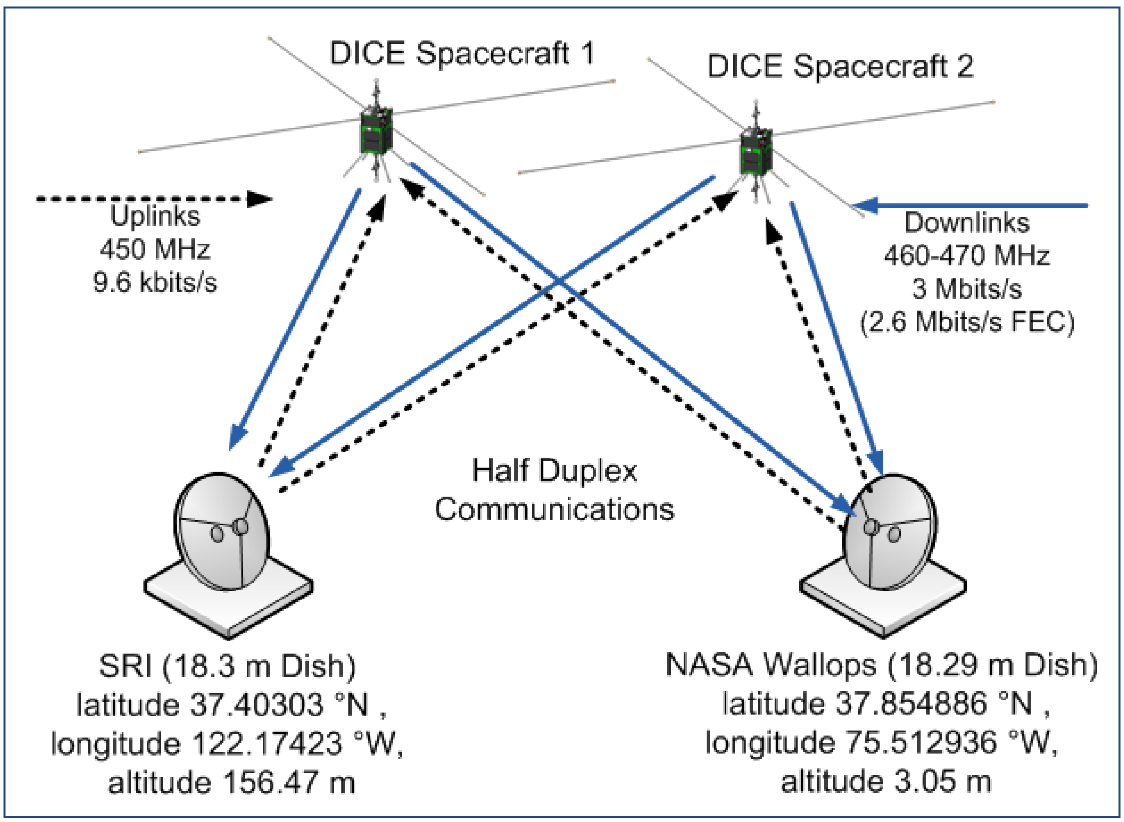

Figure 1: DICE Communication Architecture

Table 1: DICE Communication Systems Size Weight and Power

DICE Communication Systems	Mass (gms)	Dimensions (cm)	OAP (mW)	Peak Power
Receiver (Cadet)	< 200	6.9x7.4x1.35	141.6	141.6
Transmitter (Cadet)			372.8	11298.0
Interface Electronics	35	9.6x9.6x2.0	30.0	30.0
UHF Antenna	92	1.9x1.8x21.35	-	-

The Cadet radio was connected to a set of four monopole antennas which function as an omni-directional array on the spacecraft. The impact of the Cadet radio on the DICE systems was extremely low given the capabilities it provides. The size weight and power of DICE telemetry system is given in Table 1.

The Cadet radio for DICE was configured to make use of radio frequencies in the UHF band which are allocated for government. The Earth-to-Space link is a tele-command service for the DICE spacecraft, controlling the onboard spacecraft modem and internal modes of operation within the spacecraft itself. This link is at 450 MHz and is covered by the National Telecommunications and Information Administration (NTIA) footnote, US87, which states:

"The band 449.75-450.25 MHz may be used by Federal and non-Federal stations for space tele-command (Earth-to-Space) at specific locations, subject to such conditions as may be applied on a case-by-case basis. Operators shall take all practical steps to keep the carrier frequency close to 450 MHz."

The 450 MHz frequency is between bands that do not have allocations for Earth-to-Space communications and is therefore generally used by the satellite community. The DICE mission operates 9.6 kbit/s uplink using frequency shift keying for the modulation with a forward error correction code (FEC).

The DICE mission is studying the natural phenomena occurring in the Earth's upper atmosphere. It therefore fits into the category of Earth Exploration-Satellite Service as defined by the NTIA Red Book. The high speed Cadet downlink is configured for the band 460 to 470 MHz for which Space-to-Earth communications are permissible on a secondary basis provided they do not interfere with the primary users of the band. The note US201 gives additional information and places a power flux density limit on the emissions. This note states:

"In the band 460-470 MHz, space stations in the Earth exploration-satellite service may be authorized for space-to-Earth transmissions on a secondary basis with respect to the fixed and mobile services. When operating in the meteorological-satellite service, such stations shall be protected from harmful interference from other applications of the Earth exploration-satellite service. The power flux-density produced at the Earth's surface by any space station in this band shall not exceed -152 dBW/m²/4 kHz."

The 460-470 MHz band is typically not used by satellites because the limitation of working as a secondary user of the band and the possibility of interference from the primary users. However, the Cadet-U radio is equipped with the ability to control its output power to be complaint with the power-flux density requirements for use of the band by spacecraft.

LOOKING FORWARD

With the DICE mission on orbit, the SmallSat community is already turning its attention to future missions, and L-3 has been working with a number of potential customers who are interested in Cadet SmallSat radios.

Demand for SmallSat radios is coming from universities but also, quite persistently, from NASA, and the intelligence and military space communities. The general trend in these requests is simply to provide a radio link between the satellite and the ground. Requirements for the communication link are usually not very specific, and the unstated assumption is that the system integration needed to integrate the communication system with the rest of the space and ground systems can be done after the radio is delivered. However, developing the ground station and integrating it into an existing infrastructure is a task with many pitfalls that can effect performance, cost and program schedule.

Part of the reason systems integration is left until the end, is that the communications infrastructure for SmallSat missions is not well established as the technology is still maturing. There are few standardized Concept of Operations (CONOPS) for the community. Additionally, every program is trying to save money, and spending funds to define CONOPS upfront is not a high priority.

A little time and effort spent by the community as a whole, to define and implement a basic communications infrastructure, and to identify effective CONOPS, would go a long way towards increasing the level of performance of all SmallSats missions, and lowering their overall cost.

A major test for the small-sat community is whether or not we can deliver on performance and innovation, while keeping the costs in a range where the small innovative players can participate. If we can offer that balance of capability and cost, we will have a much better chance of sustained growth in SmallSats.

As a community, we have an advantage because, unlike big space, the community is still in the early development stages, and the infrastructure for small-space is not yet established. Therefore, we can take a fresh look at the enterprise, apply lessons learned, and build an infrastructure that is efficient and cost-effective, while also supporting innovation.

If we do not build a cost effective, adaptable architecture, the community will always struggle to integrate individual missions, with each mission developing its unique communication systems, and supplying its own ground infrastructure. By implementing a cost effective architecture, the community can focus its resources on developing innovative technologies, without the overhead burden of infrastructure development.

The next section addresses two fundamental questions regarding SmallSat communications:

- What are the communication infrastructure needs of future missions?
- How can the community build a communication infrastructure that affordably meets those needs?

COMMUNICATION INFRASTRUCTURE NEEDS

Before discussing communication infrastructure, this paper summarizes the current CubeSat launch infrastructure, as an example of how infrastructure can work beneficially for a community, even if it is not an ideal system.

Existing Launch Infrastructure

The majority of SmallSat launches ride piggy-back on larger rockets used for launching full-size satellites. For example, on October 28, 2011, a Delta II rocket launched the NASA Suomi National Polar-orbiting Partnership spacecraft, with six additional SmallSat missions onboard. Once the NPP satellite was deployed, the SmallSats were deployed from the Cal Poly- developed Poly Picosatellite Orbital Deployer (P-POD) launchers.

The P-POD launchers are standardized mechanical systems for mounting SmallSats within the primary launch vehicle, and for pushing the SmallSats away from the rocket structure, once the desired orbit has been reached.

The launch vehicle system and P-POD on-orbit launcher constitute an infrastructure with many inherent benefits for the low-cost SmallSat missions. The larger launch vehicle and its associated mission support systems provide the physical systems and operational processes for launching SmallSats with minimal added mission cost – far less than any dedicated SmallSat launcher. The P-PODs provide the standard interface, with the added benefit of scalability (supporting 1U through 3U SmallSats), and simple design.

The infrastructure provided by these systems is not ideal, since the SmallSat launches are completely dependent on the launch schedule of the primary payload, and typical large satellite launches can be delayed for many months, for any number of technical or programmatic reasons. Also, the SmallSat orbits are determined by the launch trajectory to achieve the desired orbit for the primary satellite. However, the community has learned to adapt to these constraints by being flexible.

Communication System Infrastructure Objectives

As we look at possible options for a SmallSat communications infrastructure, it would help to identify the SmallSat community's overall objectives. The following list, while not vetted by the SmallSat community, is meant as a starting point for future discussions.

Tailored to SmallSat Needs

Infrastructure for SmallSat missions should be tailored to some extent to typical needs of the SmallSat community. SmallSat missions are at the lower end of the cost and complexity scale, so the infrastructure should also seek to have lower cost and less complex systems. SmallSat mission teams typically consist of small numbers of personnel, and personnel are trained in multiple mission tasks.

Scalable and Adaptable

The infrastructure should be scalable and adaptable in order to support a growing user base and a broad range of mission needs. Domestic SmallSat growth outlook is strong based on new programs coming out of NASA and the defense agencies. International SmallSat growth looks strong as well. Also the diversity of missions is increasing with several programs looking to SmallSats for affordable LEO constellations, and tests of planetary mission technologies.

Support Rapid Development and Deployment

One of the important benefits of SmallSat missions is their relatively short development time and ability to rapidly deploy new systems and technologies. The infrastructure needs to support this rapid development approach.

- Horizon: five to ten years
- Emphasis on LEO SmallSat Missions that can benefit from infrastructure

Having provided a set of notional community objectives, we can now outline the SmallSat communication infrastructure objectives.

For this discussion, we will divide the infrastructure requirements into two categories: 1) the ground infrastructure and 2) the satellite radio. The satellite radio is not usually included in the scope of communications infrastructure, however, its physical, electrical and signal interfaces contribute to the ease of system integration and the overall infrastructure plan, and so they are included here.

Ground Station Objectives

Networked Ground Stations

Ground stations should be networked so that the telemetry, tracking and control (TT&C) and data downlink functions are not constrained by the geographic location of the mission operations team.

NASA already supports a number of networked ground stations including the Near Earth Network and the Deep Space Network. The Universal Space Network is another network of ground stations that is privately run, and supports government and private enterprise missions. SmallSat missions have already tapped into these networks and have received excellent support.

However, there are potential advantages to pursuing a ground network that is tailored to the SmallSat community needs. The main advantages that should be considered are mission scheduling, cost, and system complexity in terms of mission integration and operations. These advantages have been described in detail in previous technical papers[1, 2].

Additionally, there are advantages to not sharing ground control systems with larger and more costly space missions. The more costly missions will almost always have priority over SmallSat missions, adding a level of uncertainty to SmallSat mission scheduling and access to the ground control facilities.

Simple Hardware and Software Interfaces

Ground systems should have simple hardware and software interfaces, geared toward the simpler SmallSat mission systems. Depending on the SmallSat mission specific support equipment may need to be installed. This might be no more than a laptop, with a commercial-off-the-shelf satellite TT&C software package. Or, the mission support equipment could also be more comprehensive, consisting of a rack of electronics for specialized TT&C and data downlink functions. In either case, interfaces should be straight forward and well documented, so that a small team can integrate mission systems in a reasonable amount of time.

Reliability

Even though SmallSat systems should be simple and low cost, the TT&C and data downlink functions need to have a high degree of reliability. TT&C functions should not be degraded either by natural phenomena such as adverse local weather conditions, or human-caused degrades such as system crashes, or over-tasked schedules.

Compatibility

Ground stations should be compatible with most common frequency bands and waveforms. Additionally, the ground station should be able to operate in half-duplex or full-duplex modes. This will give satellite developers a suitable range of options for optimizing the communications system within the overall needs of the mission.

Distributed geo-locations for robustness

Geographically dispersed ground terminals will provide redundancy in case of adverse weather or other adverse conditions. Dispersed terminals will also provide more frequent opportunities for establishing ground-to-satellite links around the globe.

Multi-mission capability

The ground architecture should support multiple concurrent missions. This requirement implies independent ground antennas for tracking different satellites. Geographically dispersed ground stations can be networked to provide this capability. However, multiple antennas and terminals at a single site would provide a significant step up in capability, especially in the case of multiple satellites in close orbital proximity.

Pre-flight test and verification capability

The ground communications infrastructure should provide facilities for integration and test of communications systems prior to system deployment. The mission team should be able to connect their own mission ground systems and spacecraft systems into the communications infrastructure to test and verify end-to-end communications.

Scheduling

Much work needs to be done to optimize schedules for multiple missions. However, the fundamental requirement is that once a mission is launched, access to the ground communications network should not be delayed. For the SmallSat community, this implies that at least some elements of the communications infrastructure must be dedicated to SmallSat missions.

Direct on-site access or remote access

Mission teams should be able to work on-site at the ground station if desired, for example, if the mission team wants to have direct access to the antenna. However, the team should also have the option to work remotely if there is no need to have direct physical access to the ground terminal systems.

International access

The communications infrastructure should allow access to international missions

Optional mission unique capabilities

The overall ground communications architecture should be designed for low cost and simplicity. This may mean that the infrastructure may not have the inherent capability to support more complex mission needs, e.g., near real-time downlinks, high level security protocols, or missions that require constant contact with the satellites. However, though the ground infrastructure may not have the inherent capability to support complex missions, it should not prohibit these types of missions, through technical or policy barriers. For example, a network of SmallSat ground stations may not be able to provide 24/7 TT&C for an on orbit constellation of CubeSats. However, it should still be able to provide partial coverage to satisfy a portion of the TT&C requirements if needed. Another example is a mission requiring restricted access and encrypted links. While the ground network may not provide the specific encryption capabilities, it should have the ability to stand up a secure space and implement security protocols to support the missions that require sensitive or secure operations.

Satellite radio objectives

Assured C2 uplink (in conjunction with ground terminal)

As with the ground station, the C2 uplink should have a very high degree of reliability for the TT&C and mission data downlink functions.

Flexible design for a range of missions

SmallSat radio designs should be based on a core architecture that can be configured for a range of communication needs, and should not be designed from a blank sheet of paper for each mission. Basic design features in an adaptable core radio architecture include use of off-the-shelf components, applying commercial best practices for manufacturability, and designing circuit boards with layout options. The mission developers can configure these features at time of build, to produce a radio with capabilities tailored for specific mission requirements. These features also contribute to lower cost.

Software defined radio (SDR) features are also effective at reducing per-unit costs and improving mission adaptability. The SDR features can be applied with the firmware load during the build process. The radio can also be designed to change communication protocols while on orbit, or even to accept firmware changes on orbit.

Specific design options that can be considered are a variable rate downlink for the satellite transmitter. This is one option that should be programmable on-orbit. Although mission data downlink rates are highly dependent on the ground receiver, satellite transmitter, antenna, distance from the receiver, and frequency band, including a variable rate downlink in the satellite transmitter greatly increases the options for the ground receiver system. Low data rate satellite transmissions could be received by smaller aperture antennas. This increases the options for downloading data to receivers in different geographic locations, and also opens the possibility of down-linking to remote or portable terminals.

Store and forward using onboard transmitter memory is another option that should be considered for SmallSat radio design. The store and forward architecture consists of pre-processing and storing mission data in the transmitter's memory. When the satellite passes over a suitable ground station, the stored data can be bursted down in a very short time period. This is a power efficient design that is well suited for LEO missions that gather data over one or more orbits then send the data to a ground station when passing through the contact window.

Full or half duplex architecture is another consideration. Half duplex communication architectures generally have lower SWAP than full-duplex architectures. Half-duplex architectures can also approximate full-duplex capabilities through timing protocols.

Finally, frequency bands, peak data-rates, modulation, and waveforms are all link characteristics that are highly mission dependent. Satellite radios that provide some level of flexibility with these parameters will help mission planners optimize performance while keeping developments costs at a reasonable level.

Simple interfaces

Similar to ground station interfaces, simple but adaptable software and hardware interfaces between the satellite radio and the satellite are essential to building cost effective systems. Hardware interfaces include the physical form, attachment points, cables and connectors, and thermal regulation devices. Software interfaces include the data format and communication protocols.

NTIA spectrum compliance

In previous years, spectrum compliance with the National Telecommunications and Information Administration (NTIA) guidelines was not rigorously enforced, due to the experimental nature of many SmallSat programs. However, as SmallSats become more prevalent, and missions become less experimental and more technically mature, NTIA compliance will become a hard requirement. Accordingly, SmallSat radios will be required to implement the necessary signal filters.

Specialized Mission Capabilities

The SmallSat radio capabilities listed above cover most LEO SmallSat mission parameters for the primary ground link. However, there is growing interest in cross-link communications for constellations of SmallSats, and options for using existing larger communications satellites, such as TDRSS, as a space relay. In general, this paper suggests a modular approach to these additional communication requirements. The ground-to-space link should have a dedicated radio with high reliability. The additional complexity required for a cross-link or comms-relay should be offloaded to a second radio. The added weight of the second radio can be mitigated by efficient power system design, and less complex antenna designs. Additionally, a complex radio that handles multiple tasks increases the probability of system failure, while two separate radios improves redundancy and decreases the overall probability of a communication systems failure.

BUILDING A COMMUNICATION INFRA-STRUCTURE TO MEET SMALLSAT NEEDS

In the previous sections, this paper has outlined a set of needs for a ground network and a mission adaptable satellite radio that would serve as key elements of a SmallSat communications infrastructure. The next section will briefly evaluate how this infrastructure might be implemented over the next few years.

There is good news in this regard: key elements of both the ground network and the satellite radio infrastructure are in place, and, in fact, were recently demonstrated in the launch and operation of the SDL DICE mission. While the infrastructure is far from complete, it does represent the beginning of a framework which can expand to meet the majority of the objects stated earlier in this paper.

The Existing Ground Infrastructure

The DICE mission has demonstrated communications through both the NASA Wallops Island facility in Virginia, and Stanford Research Institute (SRI) satellite communications facility in California. The DICE mission team installed their mission-specific communication equipment at both facilities using standardized hardware and software interfaces. Highly reliable TT&C was achieved at both locations and mission data was down-linked to both locations. Additionally, the team managed the DICE mission remotely from the SDL facility in Logan, UT, through remote terminal sessions.

While the DICE mission only demonstrated operations at two ground stations at different times, the network protocols have been established for linking multiple ground stations to form a more comprehensive ground infrastructure.

Table 2: Ground Station Network Requirements and Status

Proposed Ground Requirements	Status
Networked Ground Stations	Partial – a number of universities have dedicated SmallSat ground stations NASA Near Earth Network has been used remotely to control the DICE mission
Simple standardized interfaces	In work, pending additional community involvement and convergence on acceptable standards
Compatibility	In development
Assured C2	Demonstrated
Reliable mission data downlink	Demonstrated
Flexible data rates	In development
Simultaneous mission support	Currently possible through different ground stations. Additional antennas and TT&C systems at current locations would achieve objective while reducing overhead
Pre-flight system integration and test	TBD - Additional planning and development required
Schedule access	TBD – More experience and planning required
Remote operations	Demonstrated
Distributed geo-locations	Demonstrated
International access / international ground stations	TBD – More mission experience and coordination required

Table 2 summarizes the capabilities objectives for a ground station network, along with the status of those objectives, based on recent demonstrated missions.

Existing Satellite Radio Solutions

There are a number of SmallSat radios that have been demonstrated on orbit, or are under development for future missions. This paper will present data on the L-3 Cadet NanoSat radio as it relates to the communications infrastructure discussion presented in the previous pages. The first versions of the Cadet radio are currently operating on the two DICE spacecraft in low earth orbit, and have been successfully providing TT&C and data downlink functions since the DICE launch in October 2011. The DICE Cadet radios transmit and receive in UHF, and employ a half-duplex architecture for power efficiency. The ratio of the Cadet's downlink data rate (3 Mbps) to weight (less than 200 grams) is one of the highest demonstrated on orbit for the small CubeSat form factor.

The L-3 Cadet NanoSat radio is actually conceived and designed to be a family of radios that provide adaptable solutions for a range of missions. This adaptable design is well suited as a key system within a cost-effective SmallSat communication infrastructure.

The basic design of the Cadet family of radios is based on power efficient COTS components, a highly optimized layout, and the store-and-forward architecture. This results in a very low power receiver/transmitter system. Additionally, the store and forward architecture is a very good match for the networked ground station infrastructure described earlier in this paper. This allows the Cadet radio to process and store mission data, and then burst it down to whatever ground station is available.

The basic design also allows for configuration at build of the following options:

- Half or full duplex
- S-band or UHF

The next version of the Cadet radio, which is currently under contract for development, will be a full-duplex version with an S-band downlink. Preliminary designs have also been completed for a half-duplex S-band radio, and an upgraded UHF radio, both capable of 6 Mbps downlink data rates. The current Cadet architecture can support a downlink datarate of up to 24 Mbps.

Table 3: Satellite Radio Requirements and Status

Proposed Radio Requirements	Cadet Status
Assured C2	Demonstrated
Reliable mission data downlink	Demonstrated
Flexible design for a range of missions	
- Hardware	Under development
- SDR Features	Demonstrated and Under development
Variable data-rate downlink	Under development
Flexible downlink schedule	Demonstrated via store and forward architecture
Simple interfaces (data, power, mechanical, etc)	Demonstrated
NTIA spectrum compliance	Under development
Options	
- Encryption	Demonstrated AES 256 uplink Other encryption methods are under development
- Cross links / space relay	Under development
- Off network ground stations	Under development

Table 3 summarizes the Cadet radio capabilities that make it highly suitable towards supporting and evolving with the proposed SmallSat communications infrastructure.

Both assured C2 and reliable mission data down-links have been demonstrated on both DICE satellites currently in orbit. The 'flexible design for a range of missions' and the 'variable downlink data-rate' are being developed under a current contract, and will be fully demonstrated once the new versions of the Cadet radio come off the production line in late 2012. 'Flexible down-link schedule' and 'simple interfaces' were demonstrated on the DICE spacecraft. NTIA spectrum compliance has been incorporated in the current development effort. Uplink AES 256 bit encryption has been demonstrated on the DICE mission, and feasibility studies have been completed for adding encryption to the downlink and for implementing Type 1 encryption. Preliminary designs are also complete for cross-links, space-relays, and downlinks to mobile ground terminals.

SUMMARY

The SmallSat community is steadily gaining experience with launch, payloads, communications, and on-orbit operations. The last year has seen a number of successful missions and rapidly growing interest in new missions with advanced capabilities. While these individual missions will demand much of the community's focus, we must also pay attention to the underlying infrastructure. This is especially true of SmallSat missions, which frequently have low budgets and minimal mission support personnel. As a community we have learned to pool resources and work together to launch our satellites, making the best of limited resources. We need to do the same for our communications infrastructure on the ground and onboard our satellites.

Our ground infrastructure currently consists of a few dispersed ground stations that we have started to network together. This networked capability was demonstrated very clearly by the DICE mission, which has operated from both Wallops and SRI on the west coast, and has also demonstrated remote operations at the SDL facility in Logan, Utah. In the near future, the addition of more ground stations and greater network connectivity could make low-cost plug-n-play SmallSat missions a reality.

On the space side, the Cadet radio is a clear example of a communications system that has a proven track record of on-orbit performance, as well as a design that is adaptable to a range of future missions.

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